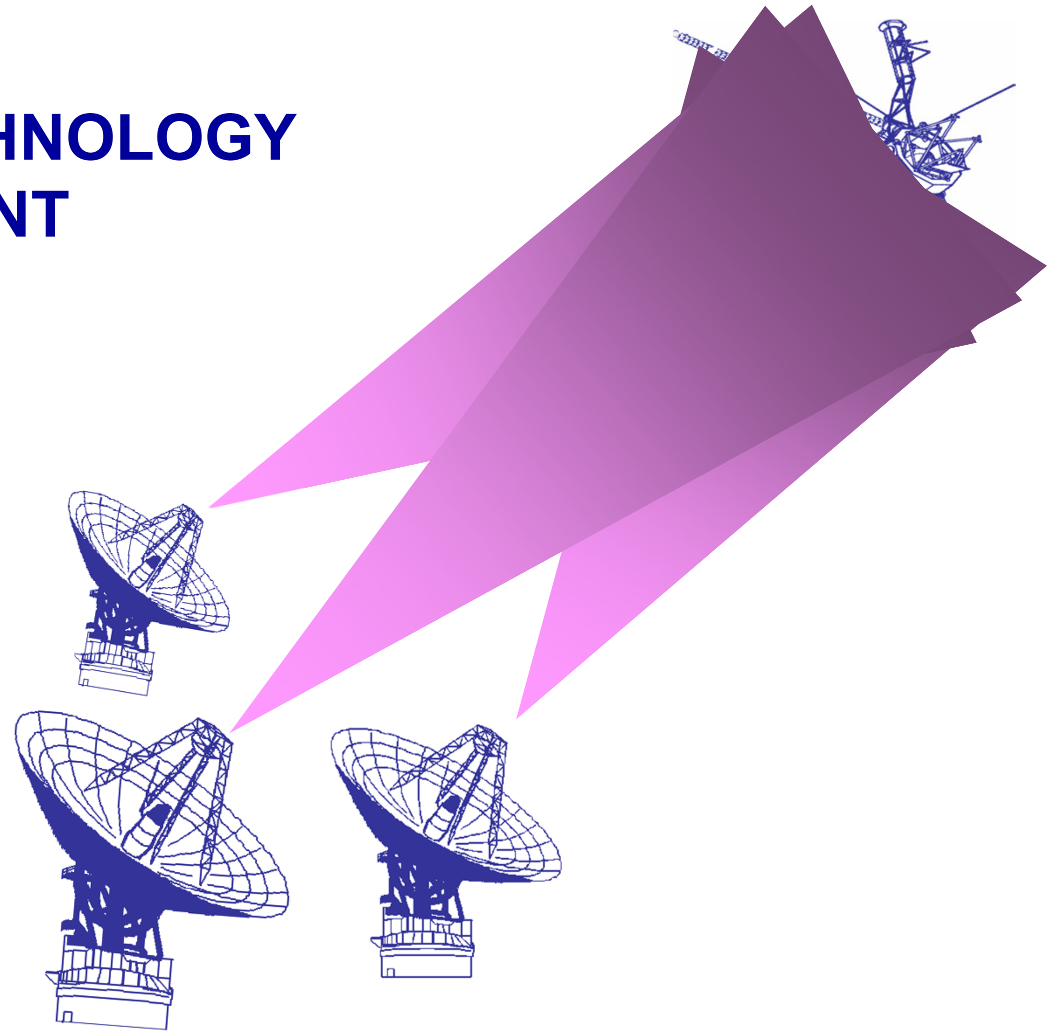
UPLINK ARRAY TECHNOLOGY DEVELOPMENT



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Philip Tsao

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March 9, 2011

OBJECTIVE

Develop and demonstrate Uplink Array CALIBRATION and BLIND TRACKING TECHNOLOGIES at X-band, under realistic operational conditions relevant to future DSN uplink arrays

UPLINK ARRAYING TO DEEP-SPACE IS CURRENTLY BEING DEMONSTRATED AT JPL

- CALIBRATION, RE-POINTING, LONG-TERM PHASE CONTROL, AND CONTINUOUS TRACKING OF REAL DEEP-SPACE VEHICLES HAS BEEN DEMONSTRATED
- OPERATIONAL NAVIGATION: SEQUENTIAL RANGING CAPABILITY REMAINS TO BE EVALUATED
- PLANETARY RADAR IMAGING IS CURRENTLY BEING INVESTIGATED

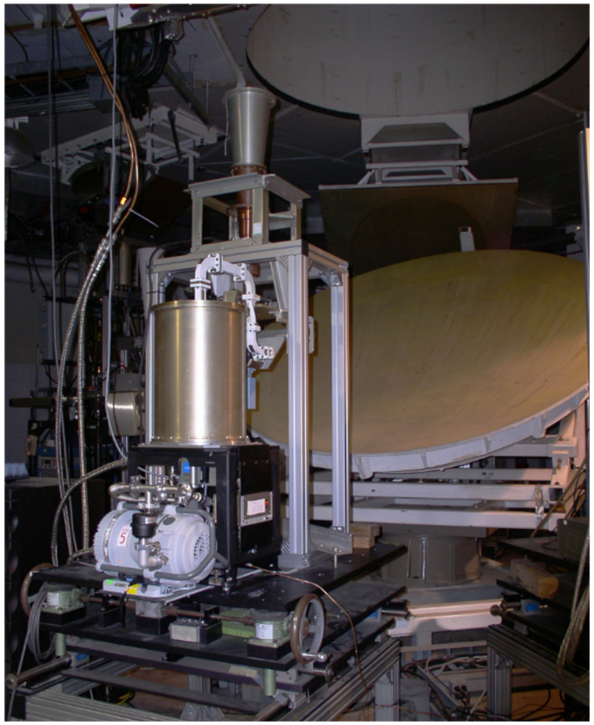
GROUND EQUIPMENT, PHASE-DRIFT CONTROL, ARRAY FAR-FIELD PATTERNS

Picture of Apollo cluster, forming transmitter part of Uplink Array (DSS-24, DSS-25, DSS-26)

- Three 34m BWG antennas, 20 KW transmitters
- Array spans ~ 500 meters
    - Antenna null-to-null beamwidth ~ 170 mdegs
    - DSS-24 – DSS-25 baseline ~ 23 mdegs
    - DSS-24 – DSS-26 baseline ~ 15 mdegs

7.15 GHz Uplink Array receiver at the DSS-13 pedestal room

- Upgraded to cryogenic LNA
- X-band output to MMS
- 321.4 MHz IF to RSR (DSS-13)
- 460 MHz IF to GSSR (DSS-14)

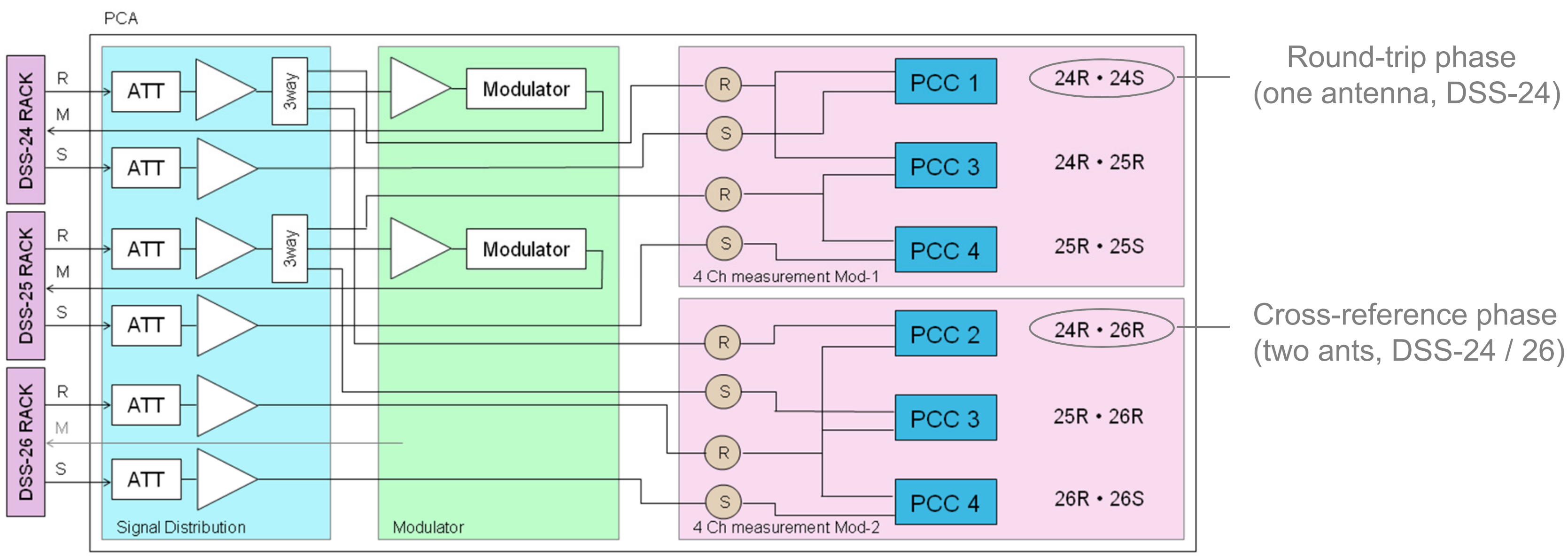


SIGNAL-DISTRIBUTION SYSTEM MONITOR & CONTROL

- Signals generated at SPC-10, distributed to Apollo cluster via ground signal-distribution system
- 16 km fiber-optic bundle provides equal transmit and return paths to and from each antenna
- Doppler-compensated carriers generated by “exciters” at SPC-10, which tend to “wake up” with random phase
- Uplink Array monitor and control system measures both “round-trip” phase and “cross-phase” between pairs of exciters
- Phase modulators in DSS-24/26 signal-paths enable real-time closed-loop compensation for ground-system phase drift

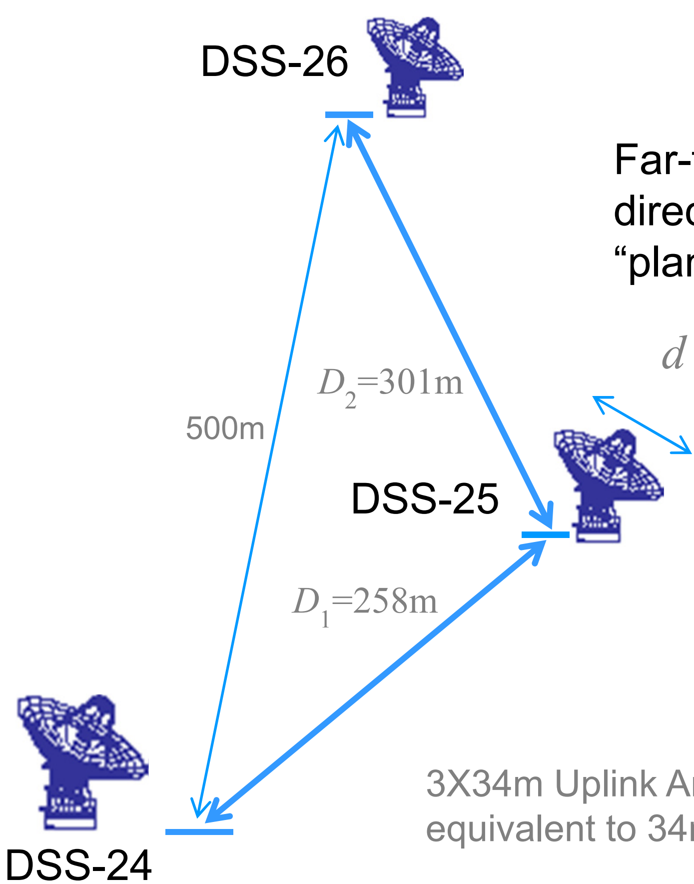
PHASE COMPARATOR COMPENSATION & CONTROL AT SPC-10

- Phase Comparator, Phase Modulator, and Signal Distribution Assemblies
- Signal itself used as reference for round-trip and cross-phase measurements

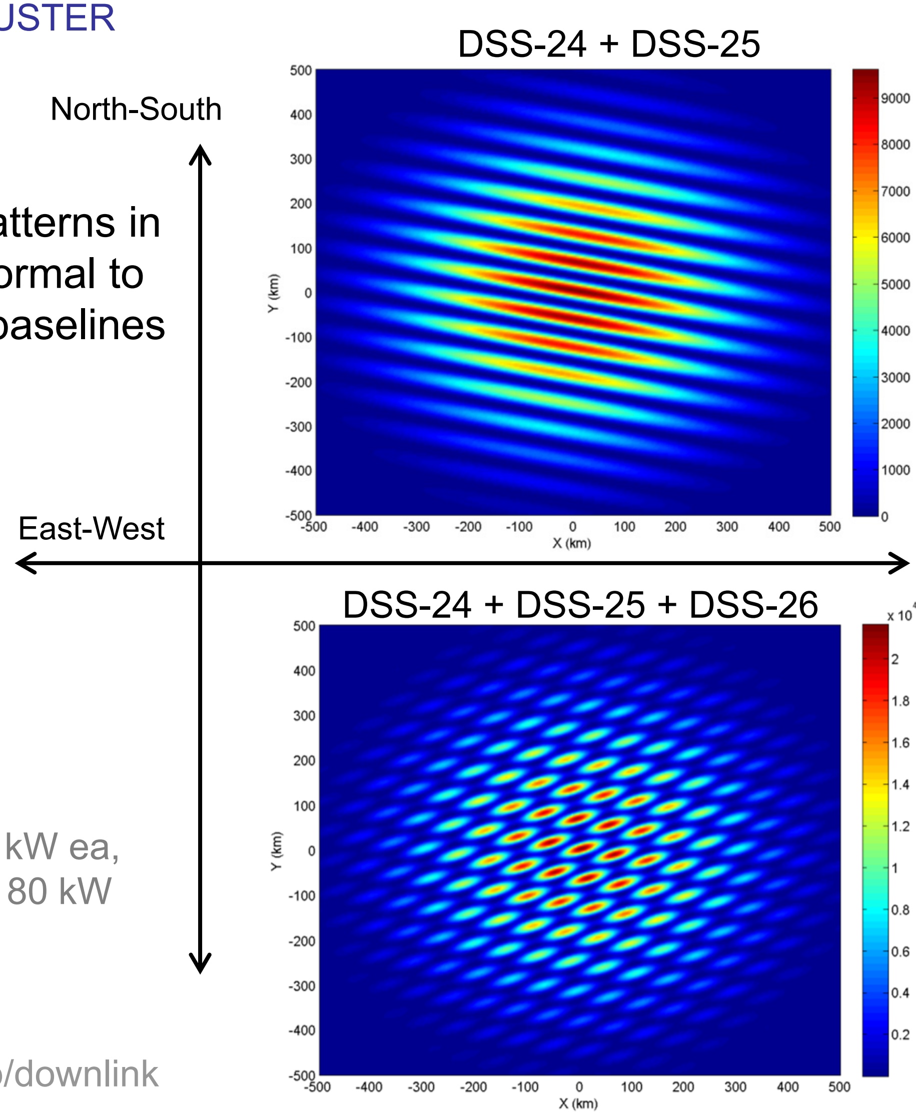


- Cross-reference measurement determines exciter "wake-up" phase AT ANY TIME
- Round-trip measurement introduces 180 deg phase ambiguity, which must be resolved

FAR-FIELD PATTERNS OF THE APOLLO CLUSTER



Far-field patterns in direction normal to "plane" of baselines



3X34m Uplink Array, 20 kW ea, equivalent to 34m with 180 kW

Uplink Array of 34m antennas
- Each element still available for single-antenna up/downlink

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FREQUENCY PREDICTS, MOON-BOUNCE CALIBRATION, CAL-PHASE STABILITY, TRANSLATION TO DIFFERENT TARGET

MOON-BOUNCE CALIBRATION SUMMARY

- The Moon is a convenient far-field radar target for Uplink Array Calibration:
  - Lunar (Az, El) trajectory similar to planetary trajectories
  - Moon visible for roughly half a day, every day of the year
  - Moon-bounce calibration requires no spacecraft signal
  - RTLT ~3 seconds enables rapid phase calibration
- Far-field calibration corrects all error sources
- After Moon-Bounce Calibration, phase-vector must be recomputed in direction of spacecraft
- Calibration phase remains stable for months

SPS frequency predicts for DSS-25: $f(t)$

Geometry-derived phase difference, $p(t)$:

DSS n, $p_n(t) = \frac{2\pi}{\lambda}\vec{\mathbf{a}}_n \cdot \vec{\mathbf{s}}(t)$

Geometry-derived frequency difference, $f_\Delta(t)$:

DSS n, $f_{\Delta,n}(t) = \frac{2\pi}{\lambda}\vec{\mathbf{a}}_n \cdot \frac{\partial}{\partial t}\vec{\mathbf{s}}(t)$

$$f_n(t) = f(t) + f_{\Delta,n}(t)$$

Pointing-based frequency predicts derived from first principles to minimize differential phase error

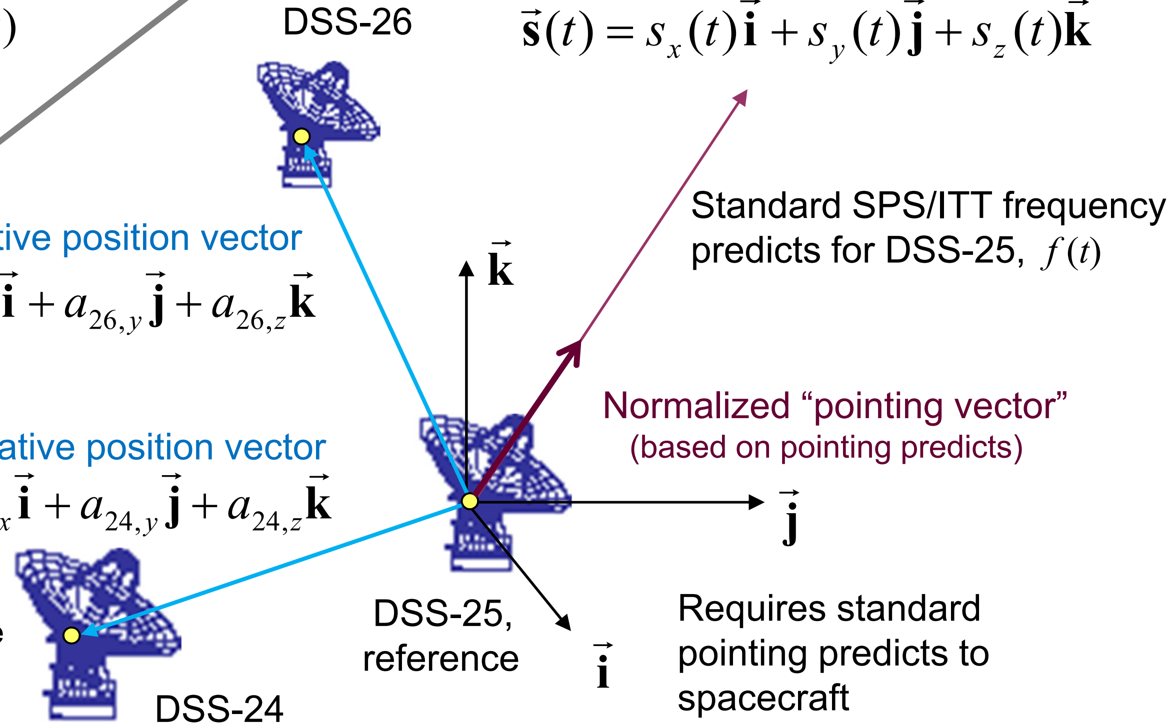
$$\vec{\mathbf{s}}(t) = s_x(t)\vec{\mathbf{i}} + s_y(t)\vec{\mathbf{j}} + s_z(t)\vec{\mathbf{k}}$$

DSS-26 relative position vector

$$\vec{\mathbf{a}}_{26} = a_{26,x}\vec{\mathbf{i}} + a_{26,y}\vec{\mathbf{j}} + a_{26,z}\vec{\mathbf{k}}$$

DSS-24 relative position vector

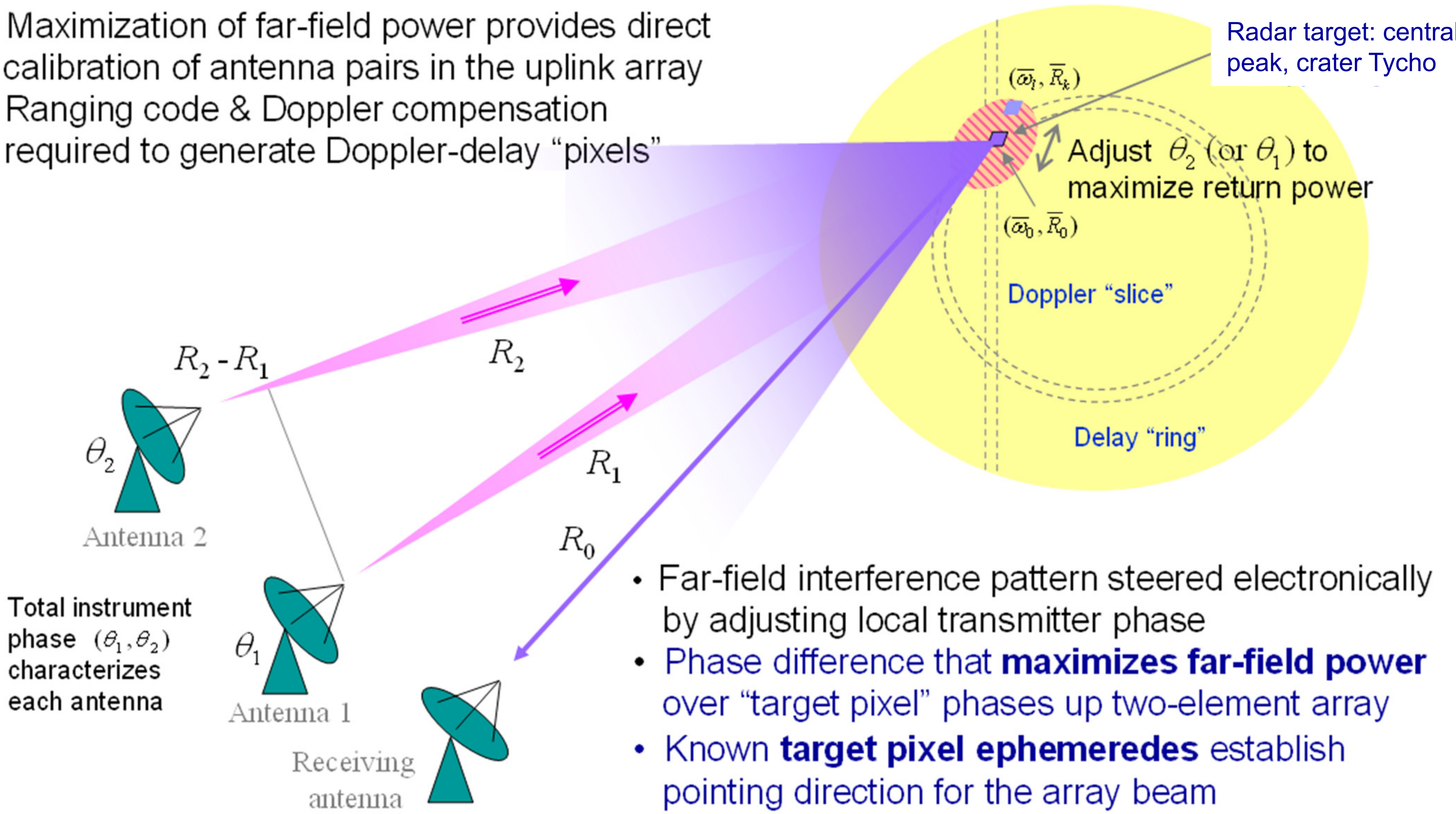
$$\vec{\mathbf{a}}_{24} = a_{24,x}\vec{\mathbf{i}} + a_{24,y}\vec{\mathbf{j}} + a_{24,z}\vec{\mathbf{k}}$$



- Precise knowledge of relative position vector coefficients is essential for accurate frequency and phase predicts
- Accurate coefficients were provided via previous VLBI solution for the DSS-24/25/26 phase centers (C. Jacobs, private communication)

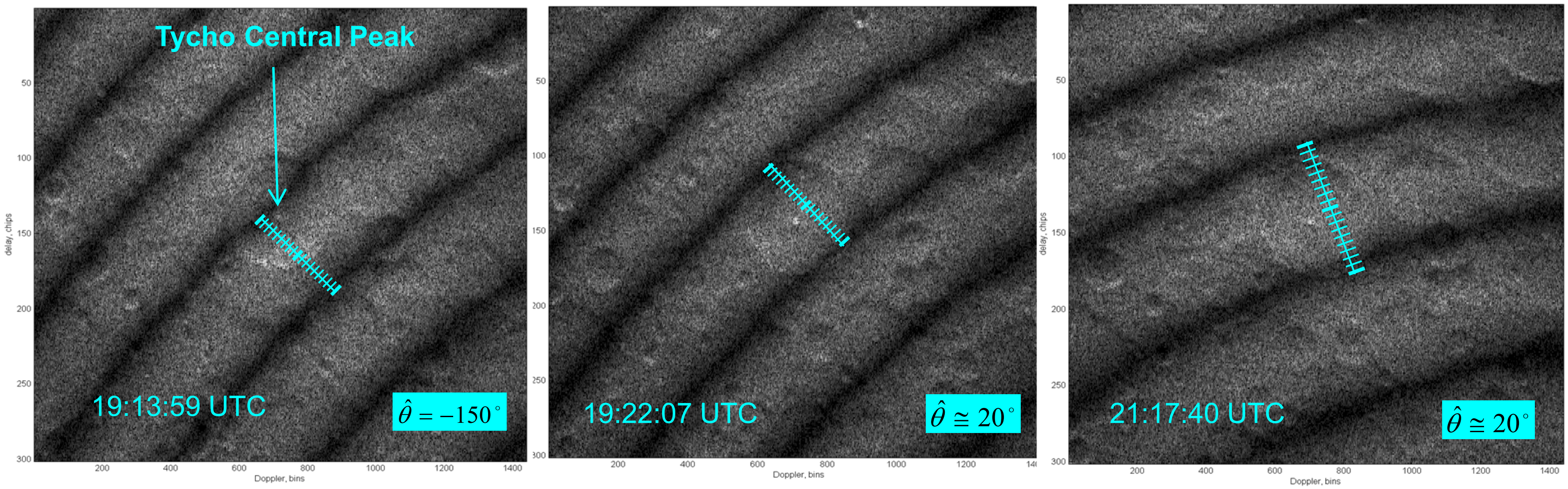
Transmit-Mode Uplink Array Calibration Technique: "Moon-Bounce"

- Maximization of far-field power provides direct calibration of antenna pairs in the uplink array
- Ranging code & Doppler compensation required to generate Doppler-delay "pixels"



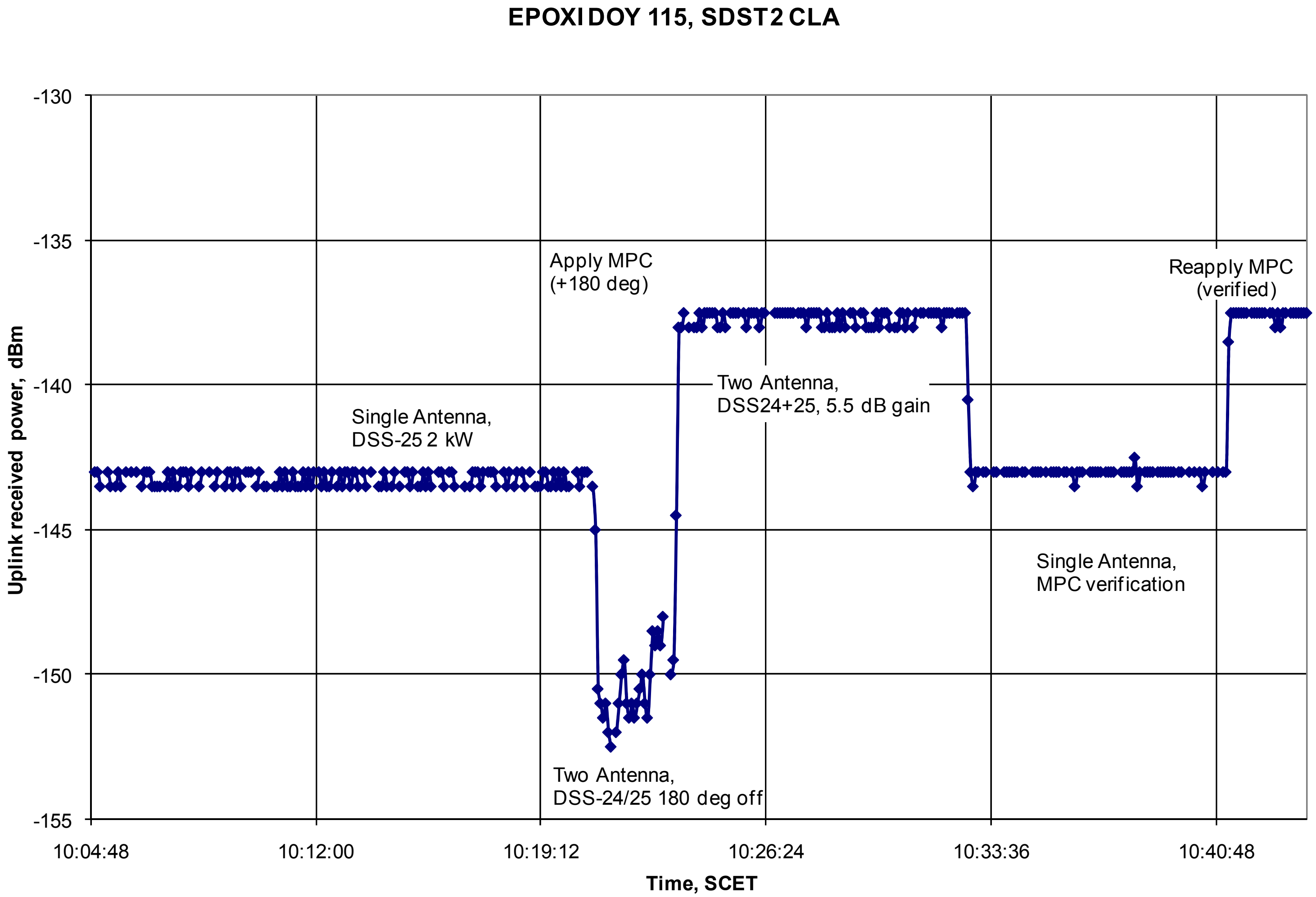
- Far-field interference pattern steered electronically by adjusting local transmitter phase
- Phase difference that **maximizes far-field power** over "target pixel" phases up two-element array
- Known **target pixel ephemeredes** establish pointing direction for the array beam

Two-Antenna Uplink Array Calibration + Far-Field Stability test (DOY-196)

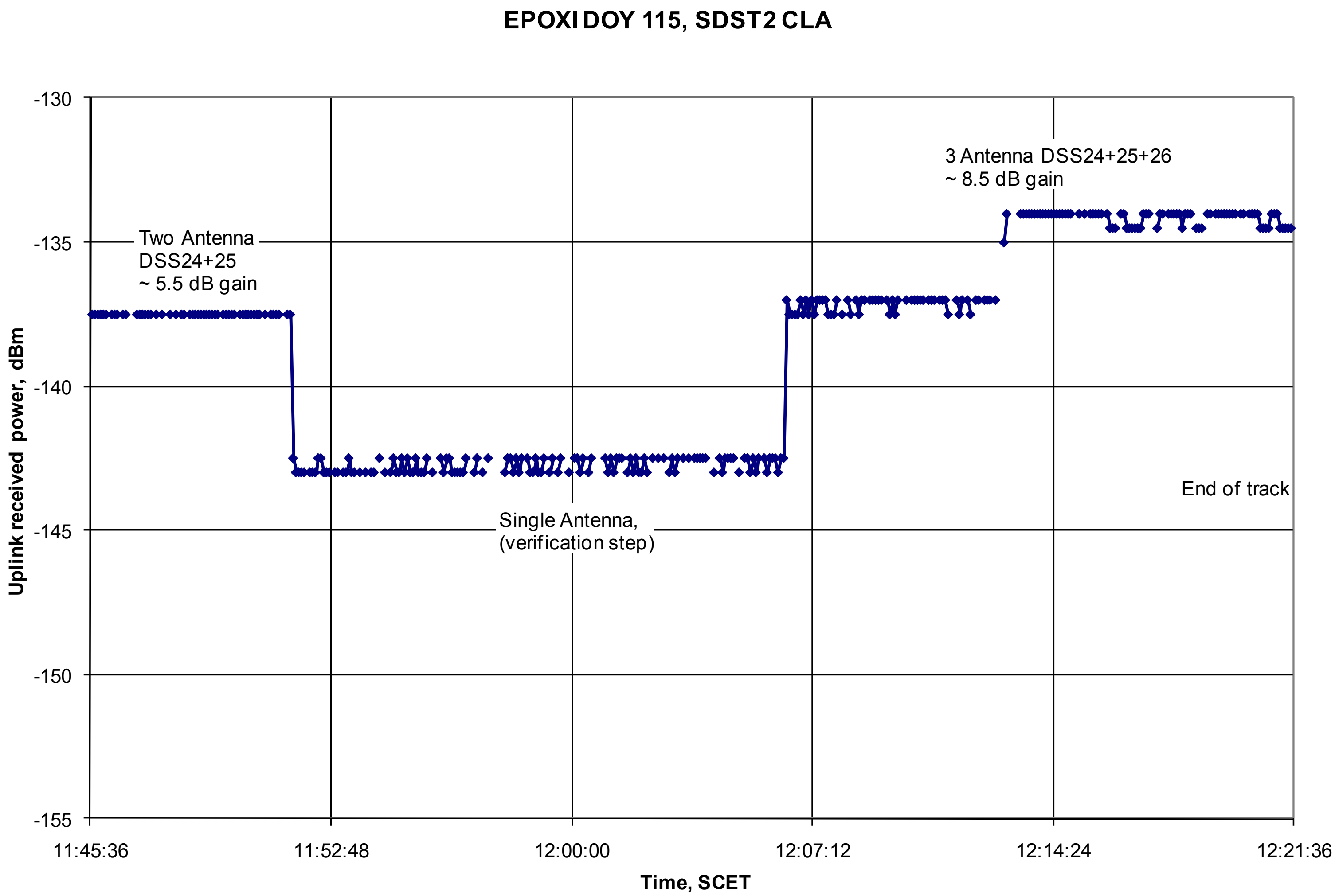


- Uplink Array calibration target (Tycho CP) initially -150 electrical degrees from fringe peak
- After rough-calibration, single correction applied to DSS-24 carrier phase
  - Phase correction placed Uplink Array fringe peak within ~ 10 electrical degrees of lunar target
- Target remained within ~ 20 degrees of peak for about 2 hours (end-of-track)
  - Real-time phase corrections were applied to DSS-24 to mitigate ground-system phase drift

EPOXI SPACECRAFT UPINK ARRAY EXPERIMENTS



First EPOXI experiment utilizing previously obtained calibration phases, and not phased up using the spacecraft itself, as in previous tracks. Validation of two-antenna calibration gain of ~5.5 dB.



Demonstration of ~9 dB gain for the three-antenna array via previously recorded MPC.

DATE	DOY	DSS-24 phase	Plus 180	DSS-26 phase	Plus 180
01/23/09	23	49	229	348	168
02/06/09	37			348	168
02/26/09	57	49	229	348	168
03/04/09	63	49	229	348	168
04/04/09	94	49	229		
04/25/09	115			348	168
05/12/09	132	49	229	213	33
06/10/09	161			243	63
06/23/09	174			288	108
08/22/09	234			240	60
10/02/09	275			355	175
10/09/09	282	202	22		
10/10/09	283	202	22		

Complete record of Moon-Bounce Phase calibrators applied since January 23, 2009.

SUMMARY: EPOXI UPLINK ARRAY CALIBRATION RESULTS

- Accurate “Moon-Bounce” calibration phase vector obtained
  - All three Apollo cluster antennas were calibrated (DSS-24/25/26)
- Coherently combined Uplink Array signals received by EPOXI
  - Coherent Lock Accumulator readings relayed to SPC-10 via downlink
- Array phasing was maintained throughout the experiment
- Theoretically expected array gains were achieved ($\pm$ 0.4 dB)
  - Nominally 4X gain for 2-antenna array, 9X gain for 3-antenna array

PLANETARY DOPPLER-DELAY IMAGING WITH THE JPL UPLINK ARRAY

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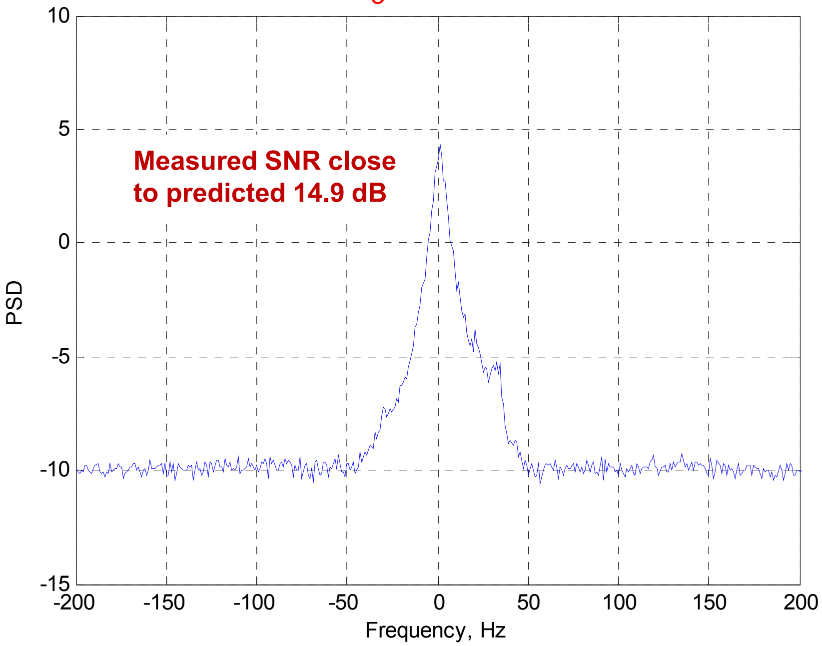
UPLINK ARRAY PLANETARY DOPPLER-DELAY IMAGING

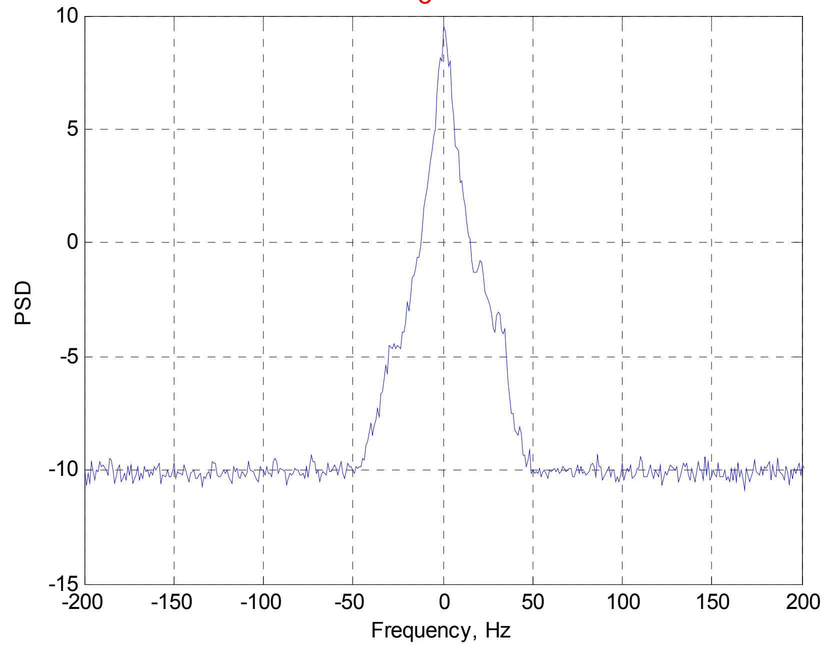
- Radar echo power falls off as fourth power of distance: $P \propto R^{-4}$
- Mercury, Venus, and Mars can provide detectable echo power with 2-3 element Uplink Array and 34 meter receiver
- EIRP of 2-element 34m Uplink Array each with 20 kW transmitters equivalent to 70m antenna with 20 kW
- Detection of extremely weak planetary echoes requires very accurate frequency and range predicts
- Uplink Array cryogenic receiver and signal processing algorithms tested on Mercury, January 25, 2010 (70m antenna,100 kW transmitter)
- First attempt to image Venus with Uplink Array occurred on October 24th, 2010 near closest approach

CW ECHOS FROM VENUS, RSR RECEIVER (DSS-13)

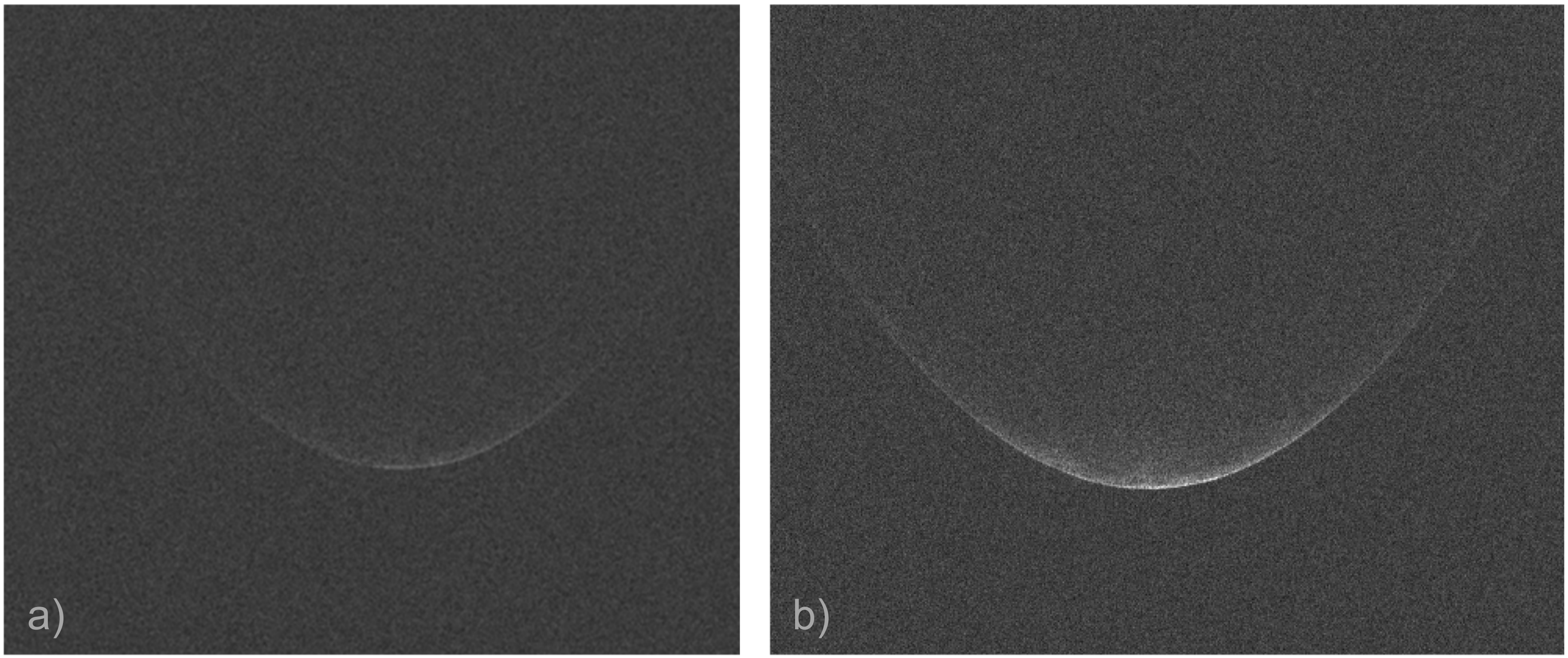
DSS25 Single Antenna CW FFT
C/N_o ~ 14 dB



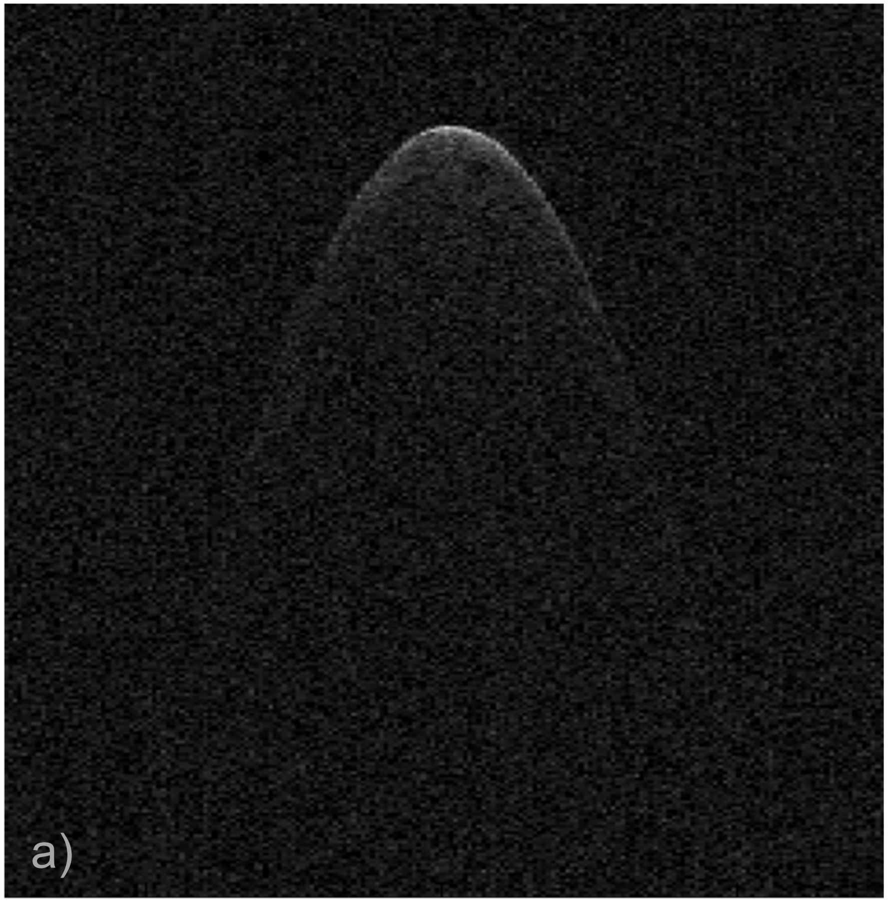
DSS24+25 Two Antenna CW FFT
C/N_o ~ 20 dB

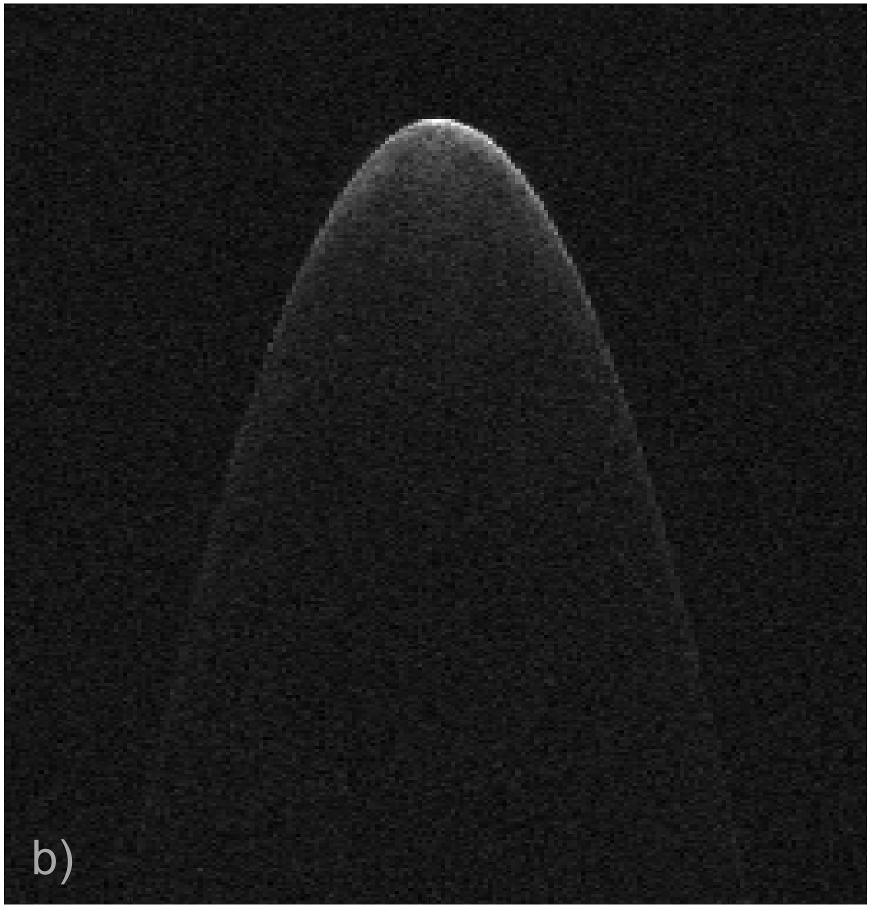


Venus echo for single and two-antenna Uplink Array illumination with RSR processing at DSS-13: SNR's of 14 and 20 dB as predicted, and demonstrating 6 dB array gain for the two-antenna array.



Doppler-delay images of Venus, taken on DOY-297, GSSR processing:
a) Single Antenna illumination (DSS-25); b) Two-antenna phased-array illumination (DSS-24 + DSS-25), showing greatly improved image quality. Range increases along the vertical axis, Doppler along the horizontal axis.

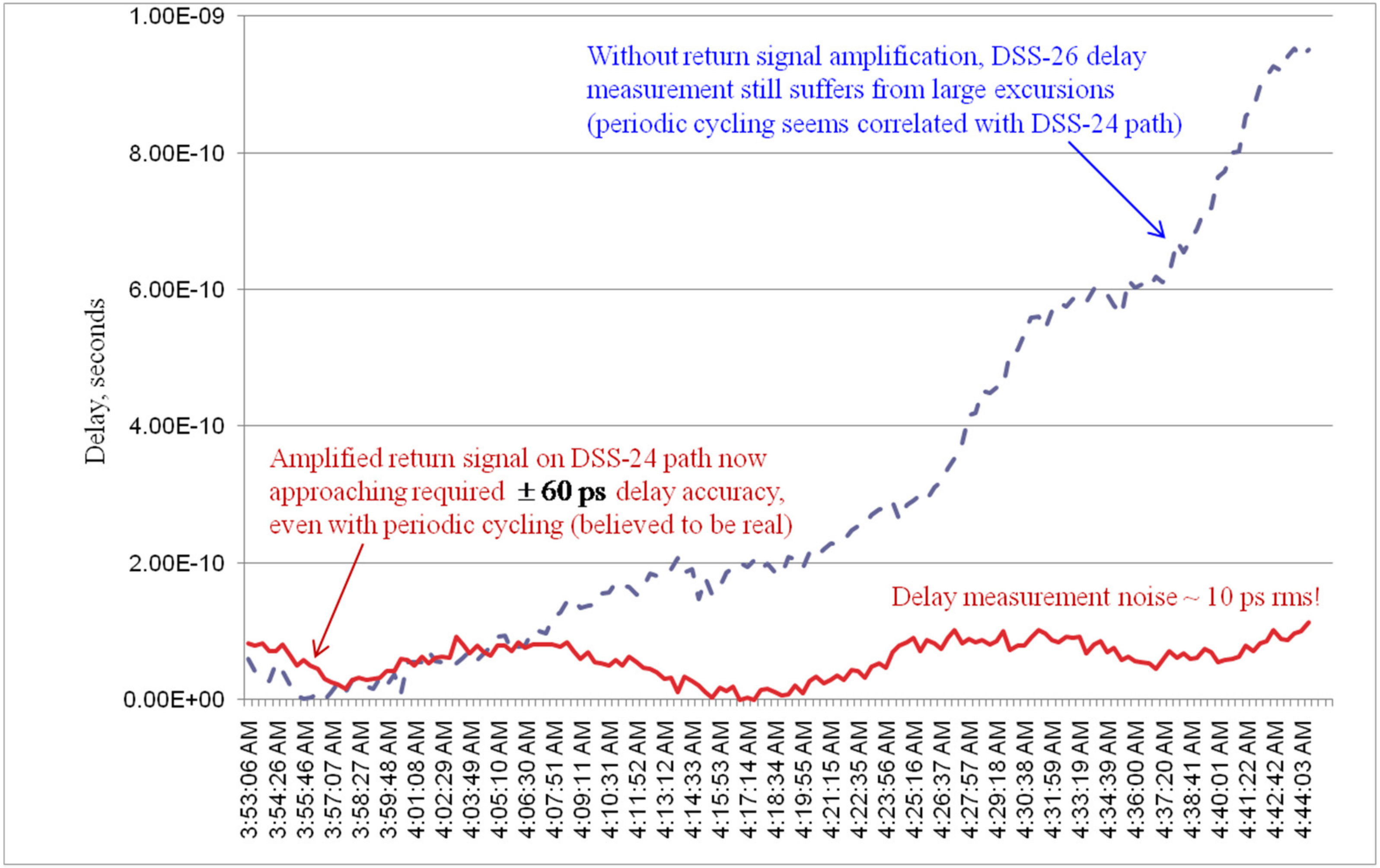




Doppler-delay images of Venus, taken on DOY-297, RSR processing: a) single antenna Illumination (DSS-25); b) two-antenna phased-array illumination (DSS-24 + DSS-25), showing greatly improved image quality. Range decreases along the vertical axis, Doppler increases along the horizontal axis.

DELAY MEASUREMENT, 180-deg AMBIGUITY RESOLUTION, TURN-KEY UPLINK ARRAY OPERATION

DOY-253 delay measurements, DSS-24/26 paths, SR-620 setup



Moon-Bounce Calibration provides a means to characterize "unmeasured phase" of the Uplink Array calibration process, without the need to disassemble parts of the operational DSN signal distribution ground-system.

- Magnitude of "unmeasured phase" remains constant, and has been determined via Moon-Bounce calibration
- Once determined, phase-offset becomes part of data-base
- Occasional Moon-Bounce updates account for aging, etc.
  - re-calibrating Uplink Array once a year should be sufficient

OPERATIONAL"TURN-KEY" UPLINK ARRAY SYSTEM CONCEPT

- Measure differential round-trip and cross-phase for each antenna pair, compensate
  - continue monitoring ground-phase drift, compensate in real-time via closed-loop system
- Measure differential range for each antenna pair to resolve 180-deg phase ambiguity
- Adjust delay in each path to compensate for initial delay differences
  - Doppler-compensation will maintain correct differential delay after initial adjustment, assuming that data/range-tones are coherently modulated onto carrier
- Apply Moon-Bounce cal-phase from data-base to complete phasing at spacecraft
- Check and update Moon-Bounce cal-phase once a year, to account for aging, etc.

REPORTS, CONFERENCE PUBLICATIONS, NTR’s

Reports, Conference publications, and NTRs to date

1. V. Vilnrotter, R. Mukai, D. Lee, “Uplink Array Calibration via Far-Field Power Maximization,” IPN Progress Report 42-164, February 15, 2006.
2. NTR # 42597: “Uplink Array Calibration via Moon-Bounce Power Maximization” (Vilnrotter, Mukai, Lee)
3. JPL News Note: “JPL Performs First Two-Antenna Uplink Array Experiment” (appeared on 3/21/06)
4. NTR # 43674: “Uplink Array Calibration Using Power Measurements from a Nearby Spacecraft” (Vilnrotter, Lee, Paal, Mukai, Cornish)
5. F. Davarian, V. Vilnrotter, “Uplink Antenna Arraying for the Interplanetary Network,” 24th AIAA International Communications Satellite Systems Conference, San Diego, CA, June 13, 2006.
7. V. Vilnrotter, Dennis Lee, “Uplink Array Experiment with the Mars Global Surveyor (MGS) Spacecraft,” IPN-Progress Report 42-166, August 15, 2006.
8. L. Paal, R. Mukai, T. Cornish, V. Vilnrotter, D. Lee, “Measurement of Antenna Phases due to Ground Equipment Effects in an Uplink Array,” to appear in IPN-Progress Report 42-167, November 15, 2006.
9. L. Paal, R. Mukai, V. Vilnrotter, T. Cornish, and D. Lee, “Ground System Phase Estimation Techniques for Uplink Array Applications,” IPN Progress Report 42-167, November 15, 2006.
10. V. Vilnrotter, D. Lee, R. Mukai, T. Cornish, P. Tsao, “Three-antenna Doppler-delay Imaging Of The Crater Tycho For Uplink Array Calibration Applications,” IPN Progress Report 42-169, May 15, 2007.
11. Doppler-Delay Calibration of Uplink Arrays via Far-Field "Moon-Bounce“ Power Maximization, V. Vilnrotter, D. Lee, R. Mukai, T. Cornish, P. Tsao, 11-th ISCOPS Conference, Beijing, May 15, 2007.
12. NTR # 44611: “Ground System Phase Estimation for Uplink Arrays,” L. Paal, R. Mukai, V. Vilnrotter, T. Cornish, D. Lee, November 1, 2006.

Reports, continued

12. NTR # 45243: "A Program for Calculating Pointing, Doppler, and delay compensation for the Moon-Bounce Experiment," V. Jamnejad, V. Vilnrotter, N. Bachman, August 2, 2007.
13. V. Vilnrotter, P. Tsao, D. Lee, T. Cornish, V. Jamnejad, "Results of EPOXI Uplink Array Experiment of June 27th, 2007," IPN Progress Report 42-174, August 15, 2008.
14. V. Vilnrotter, D. Lee, T. Cornish, P. Tsao, L. Paal, V. Jamnejad, "Uplink Array Concept Demonstration with the EPOXI Spacecraft," IEEE Aerospace Conference, Big Sky, MO, March 12, 2009.
15. P. Tsao, V. Vilnrotter, V. Jamnejad, "Pointing-Vector and Velocity Based Frequency Predicts for Deep-Space Uplink Array Applications," IEEE Aerospace Conference, Big Sky, MO, March 12, 2009.
16. V. Vilnrotter, P. Tsao, D. Lee, T. Cornish, L. Paal, "Uplink Array Calibration via Lunar Doppler-Delay Imaging," IEEE Aerospace Conference, Big Sky, MO, March 5-12, 2010.
17. V. Vilnrotter, K. Andrews, J. Hamkins, A. Tkacenko, "Maximum Likelihood Estimation of Navigation Parameters from Downlink Telemetry," IEEE Aerospace Conference, Big Sky, MO, March 5-12, 2010.
18. V. Vilnrotter, K. Andrews, A. Tkacenko, J. Hamkins, "Maximum Likelihood Estimation of Navigation Parameters from Downlink Telemetry," IEEE Aerospace Conference, Big Sky, MO, March 5-12, 2010." 12th ISCOPS Conference, Montreal, Canada, July 27, 2010.
19. V. Vilnrotter, P. Tsao, D. Lee, T. Cornish, J. Jao, M. Slade, "Planetary Radar Imaging with the Deep-Space Network's 34 meter Uplink Array," IEEE Aerospace Conference, Big Sky, MO, March 5-12, 2011.

BACKUP SLIDES

This work funded by the SCaN DSN Project: Steve Townes, Faramaz Davarian

TEAM MEMBERS CONDUCTING THE FIELD EXPERIMENT AT SPC-10

Tim Cornish (SOE, predicts delivery, SPC-10 operations, transmitter monitoring,)
Dennis Lee (downlink data, real-time display, phase estimates via “pattern-matching”, data analysis)
Leslie Paal (ground system phase monitoring, troubleshooting)
Philip Tsao (ground system phase monitoring, phase modulator control, data analysis)
Joseph Jao (GSSR receiver operation, data analysis)
Vic Vilnrotter (experiment coordination, real-time phase estimates via “phase-ramp”, data analysis)

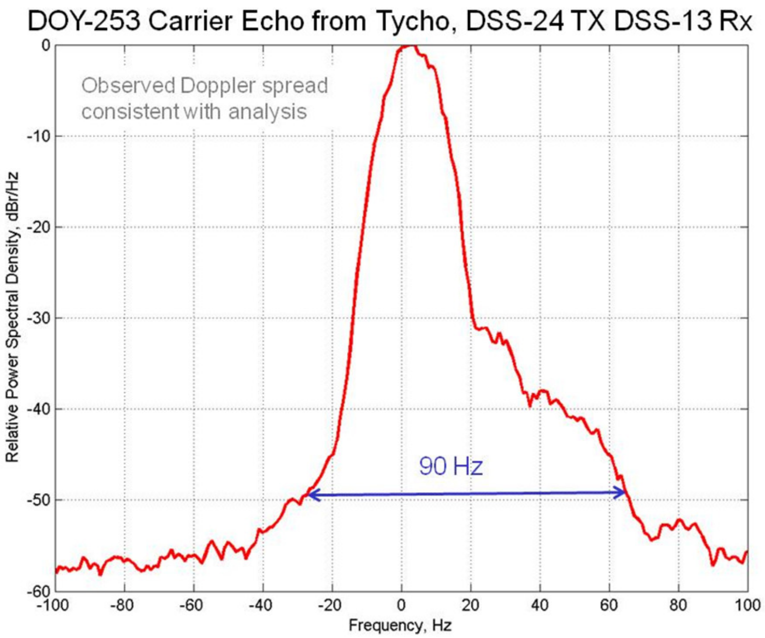
TEAM MEMBERS SUPPORTING THE EXPERIMENT AT JPL and ITT

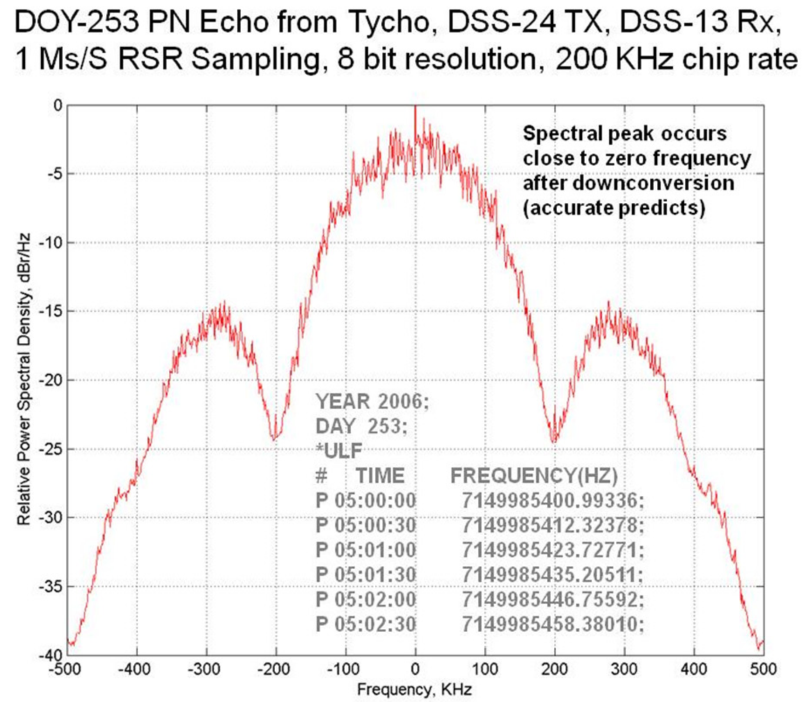
Jim Taylor (ACE, real-time EPOXI data), Al Hewitt (NOPE), Mark Carmichael (NOPE), Peter Tay (ACE)
Ryan Mukai (MER Telecom)

TEAM MEMBERS PROVIDING ANALYSIS AND CONFIGURATION SUPPORT

J. Walthers (SPS frequency predicts development), V. Jamnejad (frequency predicts development),
S. Wissler (EPOXI configuration), Hal Uffelman (EPOXI configuration), Paul Dendrenos (DSS-13)

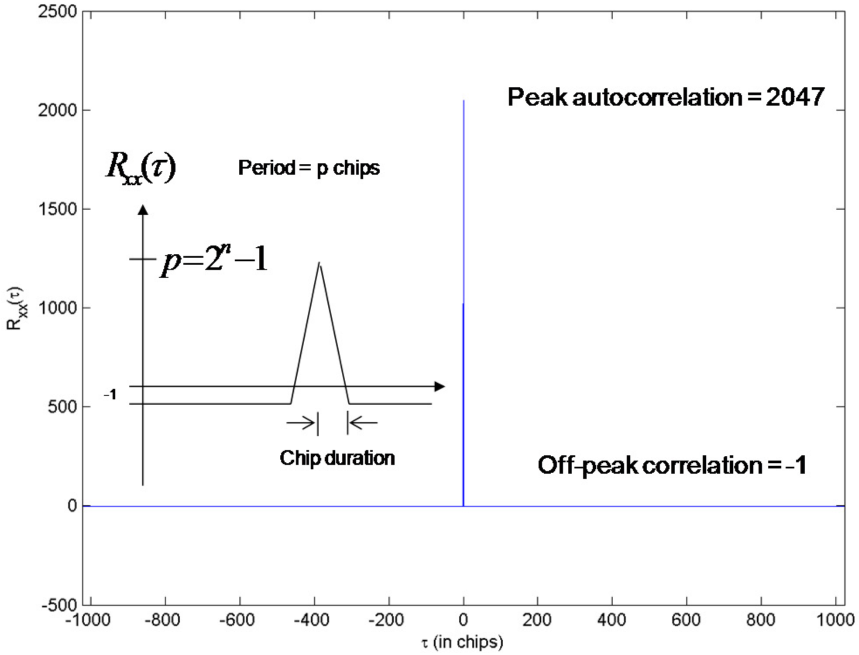
Moon-Bounce Carrier Echo Characteristics



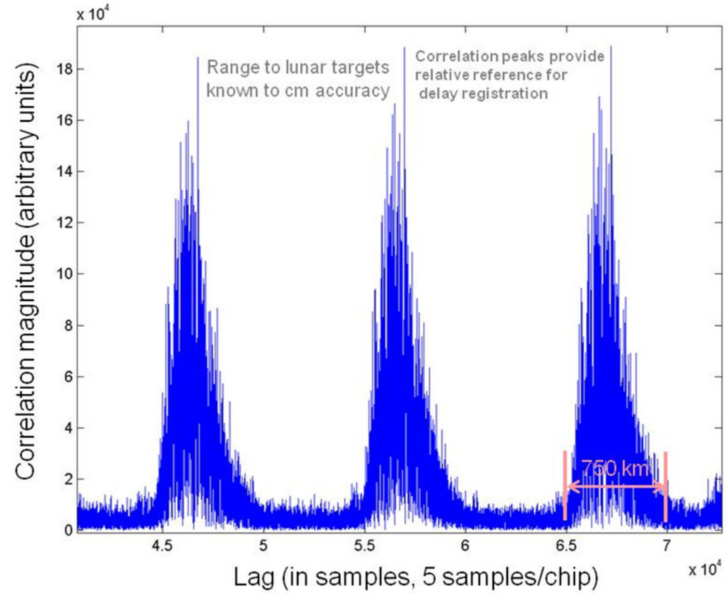


Doppler-broadened echo from the Tycho region **Spectrum of received PN-modulated signal**

PN Sequence Autocorrelation Properties



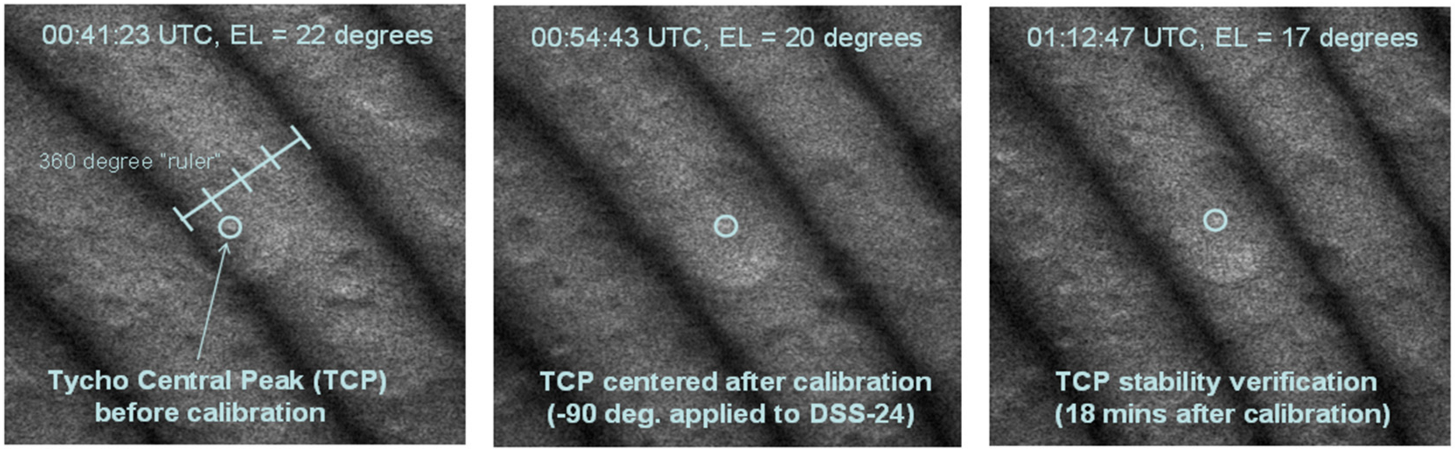
PN Correlation of return from Moon (3 sequences): DSS-25 Tx, DSS-13 Rx



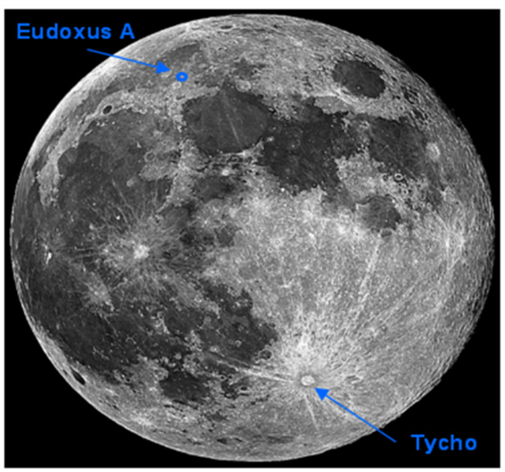
Theoretical and simulated autocorrelation function of PN11 sequence (2047 chips)

Correlation record of experimentally Observed echo from the Tycho region

CALIBRATION-VECTOR TRANSLATION DEMO; DSS-24/25, DSS-13; DOY-257



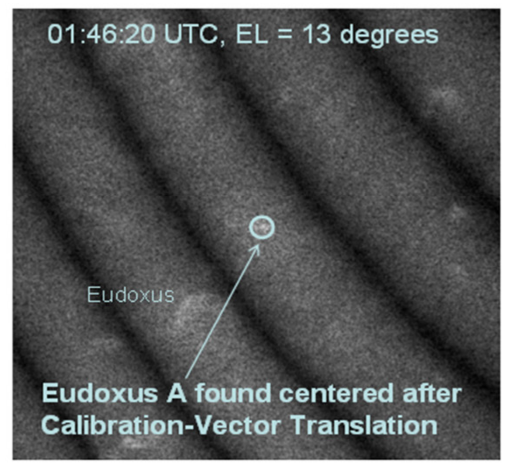
Top three Doppler-delay images: Standard calibration and stability verification via Tycho Central Peak

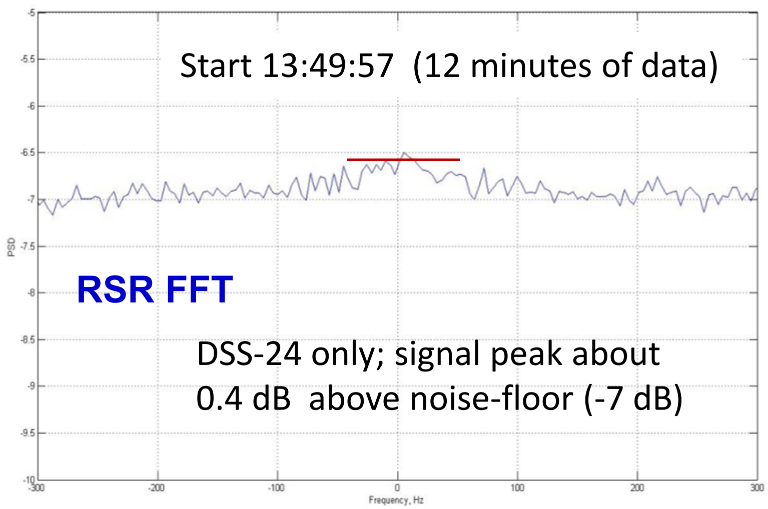


Optical image of full Moon, showing locations of calibration and vector-translation targets

Right: Demonstration of Calibration-Vector Translation concept via secondary target Eudoxus A, using computed phase and frequency predicts

Ground-phase was monitored at SPC-10, but no phase corrections were applied (phase difference remained within ± 5 degrees throughout the entire track)

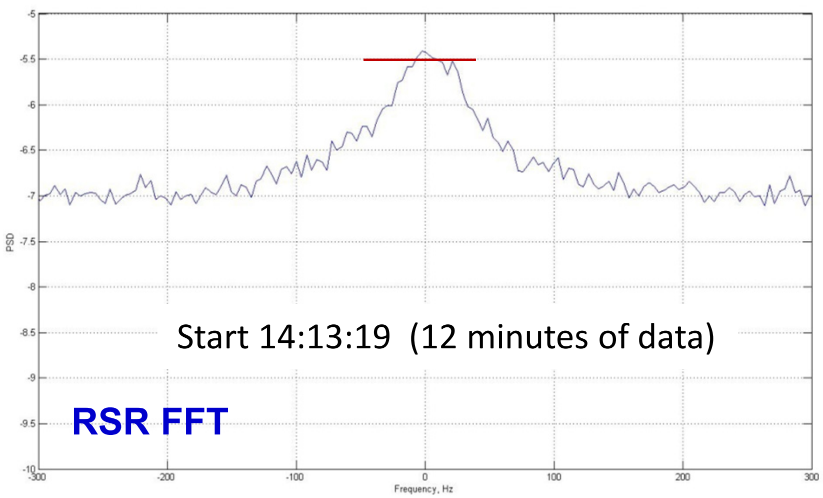


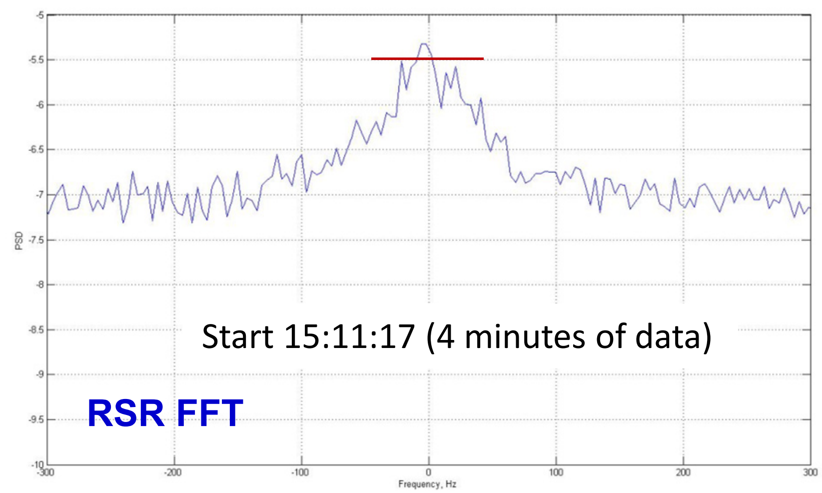


DSS-24/25 Phasing Experiment (DOY-121):

- DSS-24/25 transmitted 20 kW (carrier, PN11 code)
  - Array EIRP equivalent to 70m, transmitting 20 kW
- Successfully recorded DSS-24 carrier echo
  - Doppler-broadened carrier observed after 1 RTLT
  - RSR FFT: signal ~ 0.45 dB above noise-floor
- Successfully recorded DSS-24+DSS-25 carrier echo
  - RSR FFT: signal ~ 1.5 dB above noise-floor
  - Array combining gain: 3.7 (5.7 dB) over DSS-24
  - Array remained phased up throughout the track

DSS-24+DSS-25; signal peak about 1.5 dB above noise-floor





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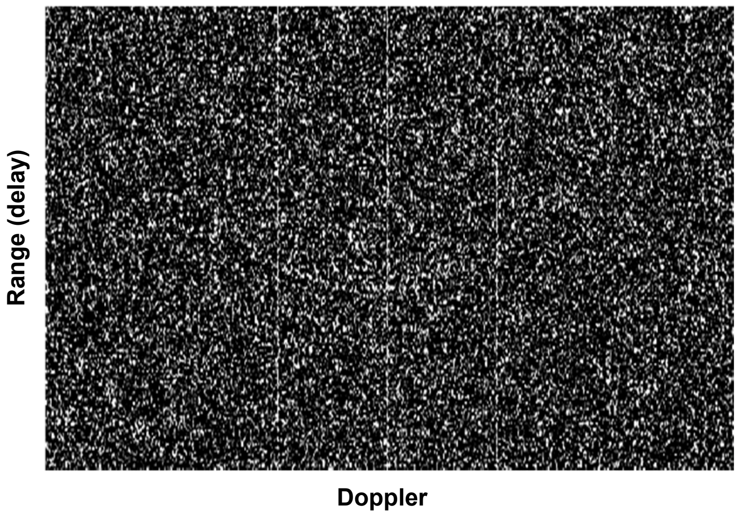
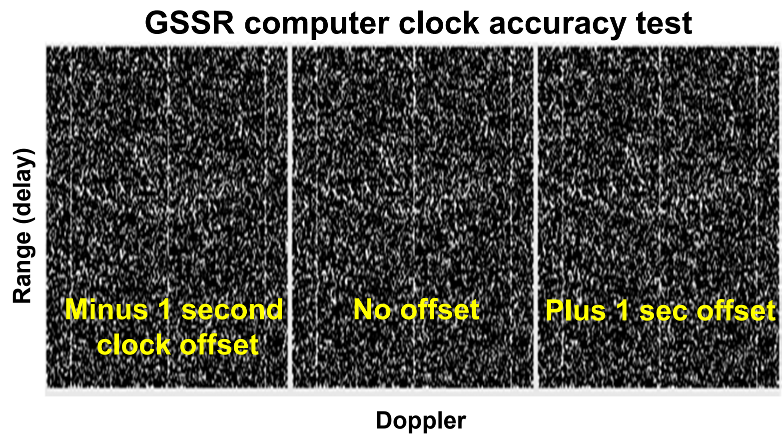
Mercury Imaging Experiment (DOY-121, 2010)

- Two 34m Apollo antennas, DSS-24/25, were phased up, transmitted 20 kW Doppler-compensated PN-modulated X-band carrier towards Mercury
- GSSR receiver at DSS-13 recorded faint Mercury signature



Original Mercury Doppler-delay image, obtained with GSSR receiver at DSS-13 on DOY-121, 1510-1550 UTC



Processed data to improve contrast, determine best computer clock setting, and extract image from data-files recorded after 1600 UTC with RSR and GSS receivers

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